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Solar Engineering
ASME 1991

FABRICATION OF THIN FILM CONCENTRATORS FOR SOLAR THERMAL PROPULSION APPLICATIONS

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Abstract

Development of Solar Powered Rocket Engine systems depends heavily on demonstrating the technology for lightweight space-deployable solar concentrators. Large elliptically-shaped thin film reflectors can be packaged with other solar-powered propulsion elements and deployed in low earth orbit. A significant step in demonstrating the feasibility of fabricating large lightweight deployable concentrators has been accomplished. Thin film casting and coating techniques for fabricating thin film concentrators have been demonstrated. These techniques have significant promise for extrapolation to large highly accurate concentrators. The concentrators achieve a low weight/area ratio and high concentration ratio by utilization of spin casting and subsequent creep and/or relaxation forming processes. These processes use newly developed polyimide materials supplied by Langley Research Center (LaRC).

This paper will summarize continuing research to develop methods to fabricate parabolic thin film membranes. The research has included selecting candidate thin film materials through a materials testing and evaluation program. Reflector fabrication and forming techniques were evaluated. Analytical models to represent forming techniques were developed. Thin film polyimide membranes using the selected techniques were fabricated. The facilities and equipment for constructing the spin cast concentrators are also presented.

Introduction

Providing lightweight, highly accurate reflectors for space applications has been a goal of researchers for many years. Thin film reflecting material formed to a precise curvature has the advantages of weight, cost, and packaging. Lightweight large reflectors have many current and future space-related applications. Solar thermal propulsion, solar dynamics systems, lunar soil processing, and large RF and microwave antennas are good examples. The use of newly-developed thin filmpolyimides to fabricate large reflectors can be applied to meet the needs of the space-related applications.

A solar thermal propulsion system with inflatable solar concentrators was originally described by Eriche in 1956 (ref.1). This concept was further defined by Electro-Optical Systems, Inc. (ref.2) during the 1960's and by Rockwell International (ref.3) in 1979. The Solar Powered Rocket Engine is expected to produce specific impulses of 900 to 1200 seconds. This is over two to three times that of conventional liquid hydrogen/oxygen engines. This performance would significantly improve travel from low earth orbit to geostationary earth orbit and other planets.

Based on past study results, the solar thermal propulsion concept (STPC) currently requires the use of two large, highly accurate inflatable concentrators. The concentrators are portions of a large paraboloid of revolution about the vehicle as shown in **Figure 1**. The shape of the concentrators is an off-axis, clam-shell-like shape. The feasibility of STPC depends of the development of a technique to fabricate, package, and deploy large, highly accurate thin film concentrators.

Constructing concentrators by seaming flat curved shape sheets together has been a relatively unsuccessful method for manufacturing accurate parabolic shapes. Typically, large inflation pressures are needed to remove the seam distortions and overall reflector inaccuracies due to the seaming methods. An alternative method investigated was to creep form seamed Kapton sheets into doubly curved off-axis parabolic shapes. The Kapton films are only available in widths much smaller than the end item reflectors that are desired. The material properties of the polyimides also vary in machine direction and with film thickness. The disadvantages of creep forming "off-the-shelf" polymer films led to investigating and developing techniques for constructing reflectors using polymer films developed by NASA Langley Research Center (LaRC) for space applications.

A thin film test apparatus was designed and fabricated to evaluate candidate thin film materials. Extensive uniaxial and limited biaxial testing of candidate film

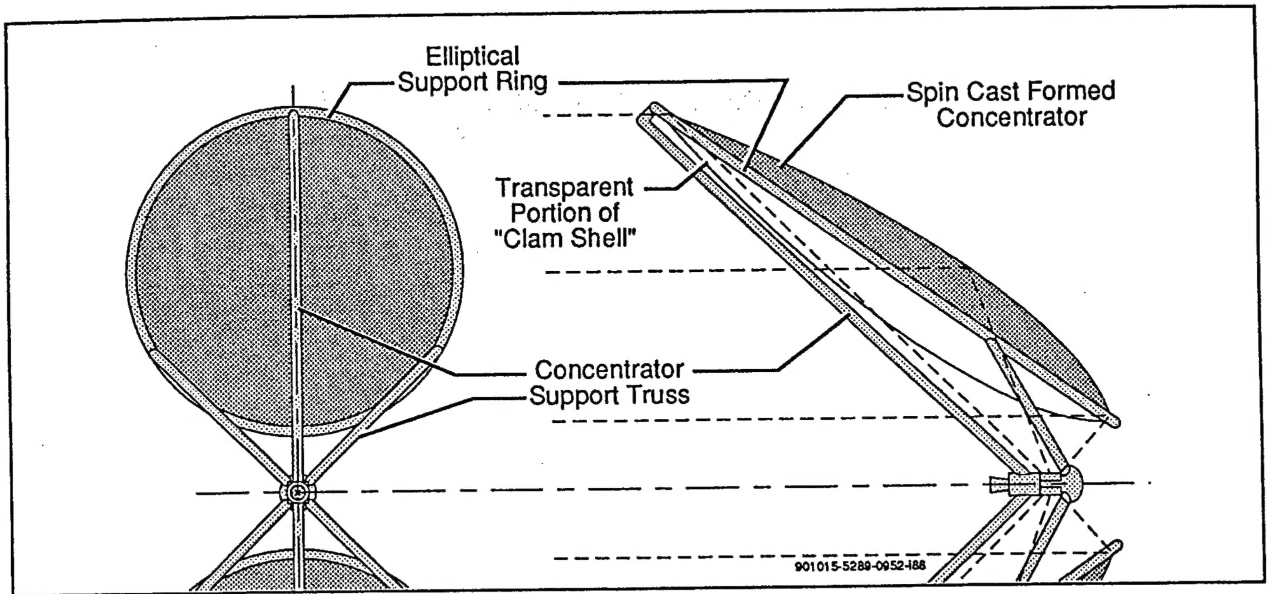

Figure 1. A Solar Thermal Propulsion Unit

materials properties was performed, and the resulting data was analyzed and compiled in a design handbook. Studies concerning specific refinement procedures for solar concentrator fabrication processes were conducted. This involved relating the data accumulated in the materials testing to the design of concentrator models constructed.

An analytical model for the membrane creep forming process was developed and utilized for the effort. It was initially intended to predict the temperature distributions of a forming oven during the pressure creep forming process. The capability of describing and monitoring other film curvature forming processes was included in the model as additional concentrator manufacturing processes developed. Physical models were built and design studies were performed to delineate problem areas in the design and fabrication of the concentrators. A creep formed spin cast on-axis reflector model was successfully constructed and tested. An off-axis mandrel cast reflector model was also constructed using the spin cast technologies.

Evaluation of Thin Film Polyimides

Candidate thin film polyimides were evaluated and selected for use in the fabrication of doubly curved reflectors. The reflector fabrication methods used depends primarily on the material properties of the thin films. The behavior of the thin film materials during the reflector forming and recovery process, as well as the long term film stability, is of importance. The forming processes are typically done at elevated temperatures between 100 and 300°C. Material properties at these elevated temperatures for commercially available films are not published and not known for the LaRC polyimides. A material test apparatus was designed and fabricated in order to test and characterize the polyimide materials. The test apparatus is used to simulate the forming processes with the candidate thin film materials.

Material Test Apparatus Description

The test apparatus that was designed and fabricated is shown in Figure 2. The test apparatus includes the necessary design features for testing the thin films. The test apparatus has many attributes which are used to test the polyimide materials used for the construction of the membranes.

The polyimide testing system is comprised of a testing machine, temperature chamber, and data logging/processing system. The testing system is capable of performing materials characterization tests such as:

- Relaxation/Recovery
- Creep
- Constant Strain Rate
- Modulus of Elasticity
- Thermal Expansion
- Cylinder Pressurization (Biaxial) Tests

A data acquisition system includes a Macintosh II which collects and stores data from several instrumentation devices. The instrumentation devices indicate the testing parameters such as oven temperature, load, pressure and strain of the material during the test. A temperature chamber is available for determining the thermal expansion/contraction coefficient. The temperature chamber can also be used for investigating the recovery of residual stresses due to the manufacturing process of the thin films. The amount of recovery is an important property that can be deter-

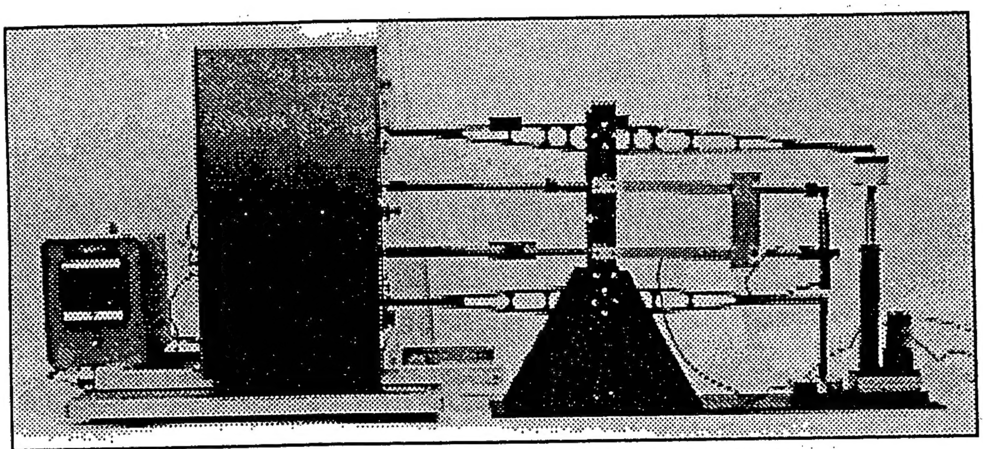

Figure 2. The Material Test Apparatus

mined and quantified experimentally with the thin film test apparatus. The complete forming processing steps can be simulated on a test sample using the test apparatus. The tests can indicate the best forming method that results in a film that is the most stable following the process. The material properties determined by the test apparatus are also necessary in constructing analytical models of the forming techniques.

Polyimide Materials Test Results

The initial testing of materials was limited to commercially available films. Kapton Type H, Upilex R and S, and Apical polyimide films were evaluated at the creep forming temperatures. The purpose of the tests was to fully characterize the thin films at the creep forming temperatures. The test results would then be supplied to an analytical model to predict the temperature variations needed in a forming oven to produce the desired parabolic shape. The undesirable test results of the commercially available films led to the investigation of LaRC polyimides.

Kapton Test Results

Kapton's deformation was defined to be "creep like" because a time-dependent strain occurs around 300°C. A typical creep curve of .5 mil Kapton is shown in **Figure 3**. Kapton also has different recovery properties in the rolled and transverse machine direction because of the manufacturing processes. The directional properties cause problems when creep forming the materials into parabolic shapes. Uniaxial creep and relaxation tests were performed using Kapton with thicknesses of .5 and 1 mil. The results of the tests indicate that there are dramatic differences in .5 mil and 1 mil Kapton with respect to creep forming the material. **Figure 4** indicates creep of 1 mil Kapton at a constant load and an elevated forming temperature. The maximum creep strain of the material during the test was less than two percent. The final strain following recovery was nearly zero percent. The graph indicates that the material has no permanent deformation under similar loading conditions which yield a permanent set for .5 mil Kapton material. Relaxation tests also indicated that the 1 mil Kapton material was not suited for relaxation forming because of the lack of stress relaxation and a large recovery of the deformation upon releasing the material. By contrast, the .5 mil material relaxed and did not recover as much strain, resulting in the desired permanent set. The test results raised many questions with regard to the material properties of Kapton at the creep forming temperatures. Material processing differences during manufacturing account for the varying material properties for the .5 and 1 mil Kapton. The test

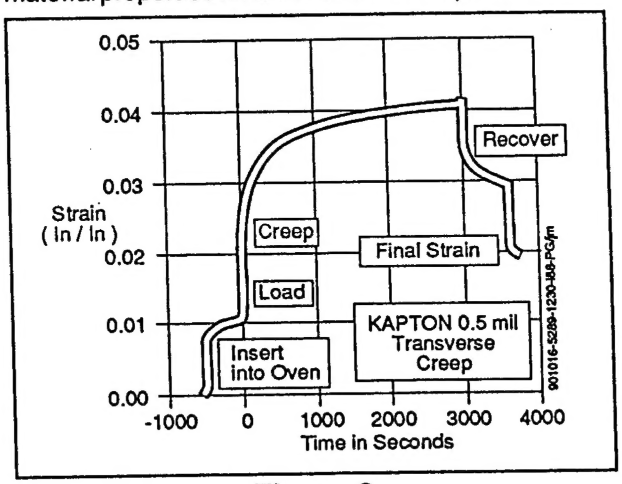

Figure 3.

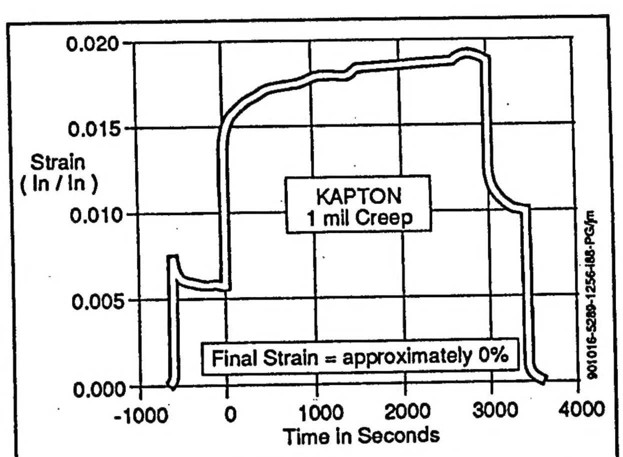

Figure 4.

results indicated that the Kapton forming properties vary with material thicknesses and manufacturing direction. These test results are detrimental when forming flat sheets into doubly curved shapes. Similar material properties of Apical and Upilex led to the investigation of newly-developed polyimides.

LaRC Polyimide Materials
The family of materials developed by LaRC include both heat imidized and chemically imidized polyimide films (ref.4). The chemically imidized is reversible; it can be redissolved and used again. Further, since the materials may be obtained in solution and then cured, any size/thickness film may be produced without seams. A spin casting technique has been used to manufacture the film in the laboratory. The film size is only limited by the size of the spin table and facility equipment.

An LaRC material used is powdered polyimide BTDA+4,4'ODA and DMAC solvent. The film is heat imidized and must be cured at temperatures around 300°C. The film acts as a thermoplastic in nature at the elevated forming temperatures. Another polyimide used is 6F+BDAF polyimide made by LaRC. This film is chemically imidized and does not require heat imidizing. This film is reversible and can be redissolved with the solvent and reused. Alternative low coefficient of thermal expansion materials are currently under investigation at LaRC. These improved polyimides may be selected for evaluation as the materials are further developed and improved.

The creep forming process of Kapton is quite different than the thermoplastic forming nature of the spin cast polyimides. The spin cast material is defined to be "thermoplastic in nature" because at a temperature of 250°C the material deforms plastically with no time dependent strain. The spin cast films also do not have the directional material variances because they are cast and cured in a circular fashion. In the spin casting process, the thickness of the film is varied by varying the viscosity of the solution used (ref.5). The surface smoothness, the characteristic that controls the achievable specularity of the reflector, is controlled by the substrate surface quality upon which the film is cast and the film stress provided while in the operational configuration.

Analytical Modeling

The objective of the analytical modeling was to develop, adapt, and refine an analytical model of the membrane creep forming process. The model was developed to enable forming parameters to be evaluated to define a process for manufacturing concentrators using the temperature profiled controlled uniform pressure creep forming process. As the project proceeded, the objective and the analytical model capability evolved to include description and monitoring of other variations of curvature forming processes such as mandrel controlled relaxation forming of polyimides.

Major milestones accomplished as a result of the modeling effort include; an extensive literature survey related to thin films, a review of software applicable to analysis of thin film structures, development of a pre/post-processor, data reduction techniques for incorporating test data into the numerical model, and finite element model development and verification. In addition to model development, techniques, and guidelines for numerically efficient implementation have been formulated.

The commercially available finite element code ABAQUS was used for the modeling effort. The capabilities of the finite element modeling were quantified for several aspects of the analysis required to support the development of thin film solar concentrators. Procedures, techniques, and guidelines were established for various aspects of modeling thin film membranes. It was demonstrated that ABAQUS could accurately incorporate geometric nonlinearity and viscoelastic material behavior into analysis of thin film membranes subjected to a variety of thermal and loading conditions.

The studies that were conducted have shown that ABAQUS modeling can be used as a powerful tool for analyzing reflector forming or other aspects of thin film reflector design. The modeling techniques have been refined to the point of being applicable to actual design problems. Additional finite element modeling is planned to model the emerging forming procedures developed for the spin cast polyimides.

Reflector Forming Methods

Ideally a thin film concentrator would be constructed to a desired shape without any seams or discontinuities. Large thin film reflectors constructed from flat stock material would require seaming because film materials are typically only available in widths less than 2 meters. Any double curving of the stock film must be achieved by processing, such as creep forming. Gores, flat or doubly curved, must then be assembled to form a large area reflector. Assembly control of all the stresses at the seam is difficult. Even if a completely stress-free, wrinkle-free, seam is achieved, the reflector is no longer homogeneous across the surface. When a stabilizing force is applied to hold or further shape the reflector this non-homogenity tends to result in flats or scalloped across the reflector, a

major source of figure error. For this reason, reflector-forming methods using spin cast polyimides were developed. Casting processes can be used that would only result in mold lines when fabricating large 20 meter concentrators.

There are a variety of methods that can be used to form parabolic membranes with the cast polyimides. Several of the techniques have been used in past research efforts to form Kapton Type H into off-axis parabolic shapes. Free forming of the membranes has been done successfully with the heat imidized polyimide material. Casting over doubly curved mandrels has also been successful with the LaRC provided materials. **Figure 5** depicts the free forming of the heat cured polyimide in the forming oven. The free forming of materials typically forms to a spherical shape with deviations toward the outside boundary conditions of the support frame. The nature of the polyimide does not form well until above the 250°C temperature. This characteristic can be used advantageously depending on the forming methods used.

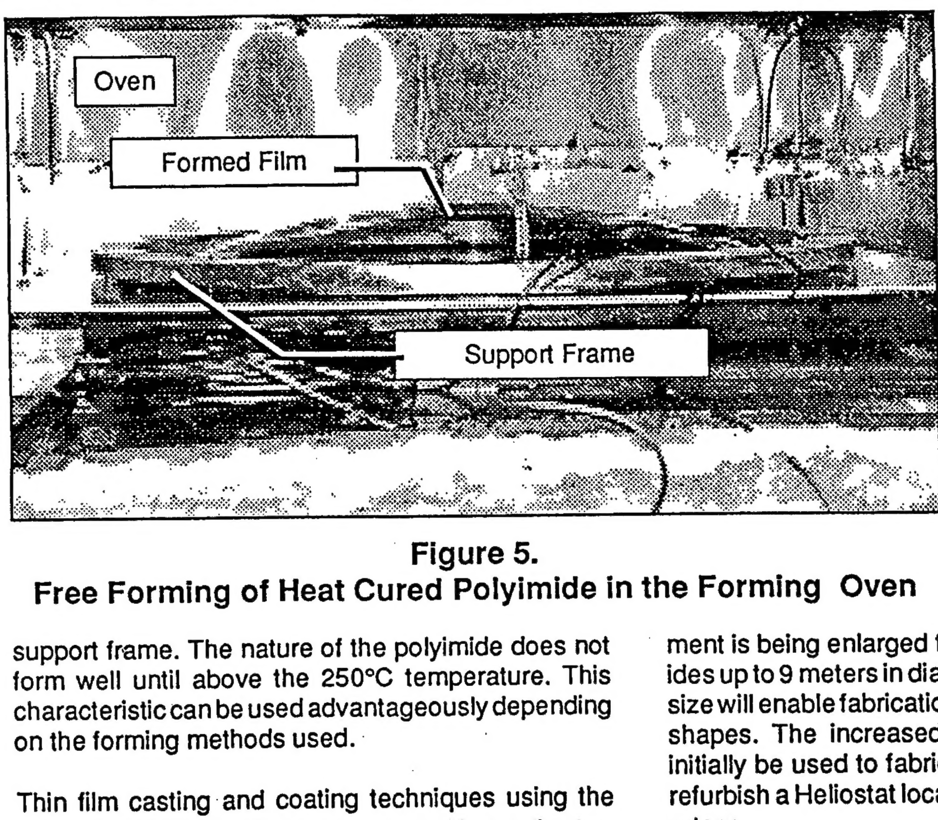

Figure 5.
Free Forming of Heat Cured Polyimide in the Forming Oven

Thin film casting and coating techniques using the LaRC thin films has been demonstrated for casting two meter polyimide films. Methods for fabricating large parabolic membranes are currently being refined. The most promising candidate forming processes, in addition to free forming, are relaxation forming over a mandrel, and direct film casting and removal from a mandrel. These casting processes have significant promise for expansion to large 10-20 meter concentrators.

Casting and Forming Hardware

The equipment required for the spin casting and heat curing of the polyimide, which are presently available, are a spin table, clean room, and heat curing oven. The facility and equipment are shown in **Figure 6.** The equipment resides in a high bay facility and is presently being enlarged to cast up to 9-meter diameter one-piece membranes. The spin table shown in **Figure 7** is currently used to cast films up to 2 meters in diameter. The spin table has been used to cast the films flat as well as casting on off-axis and symmetrical mandrels.

The spin table is enclosed in a clean room to minimize dust particles that collect during the film casting process. The clean room incorporates a positive flow environment control method. The casting of the film requires low humidity which can be achieved with the ventilation system. A positive flow system keeps the concentrations of the evaporating fumes well below safety standards for the off-gassing of solvent fumes. The insulated curing oven is convective and radiant heated. The oven temperature can be controlled to 320°C. The oven includes a door opening and sliding track system to interface curing and forming table.

The current casting equipment is being enlarged to cast one piece thin polyimides up to 9 meters in diameter. The increased casting size will enable fabrication of large polyimide parabolic shapes. The increased size of the equipment will initially be used to fabricate large flat membranes to refurbish a Heliostat located at the Astronautics Laboratory.

Conclusion

The results of the research to date have led to fabrication of spin cast, one piece, polyimide concentrators without seams. Analytical models have also been developed to evaluate forming operations. A material test apparatus was also constructed that will support continued refinement of polyimide casting materials. Fabrication procedures have also been developed that will be extended to larger polyimide casting. The

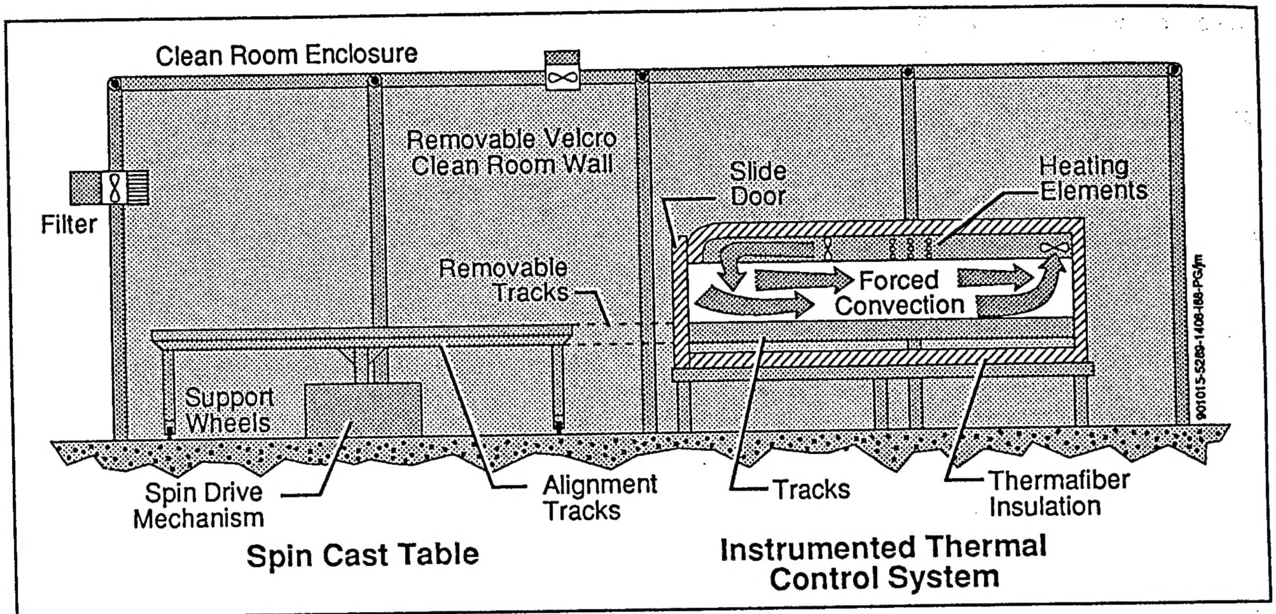

Figure 6. Clean Room with Spin Cast Table and Instrumented Thermal Control Systems

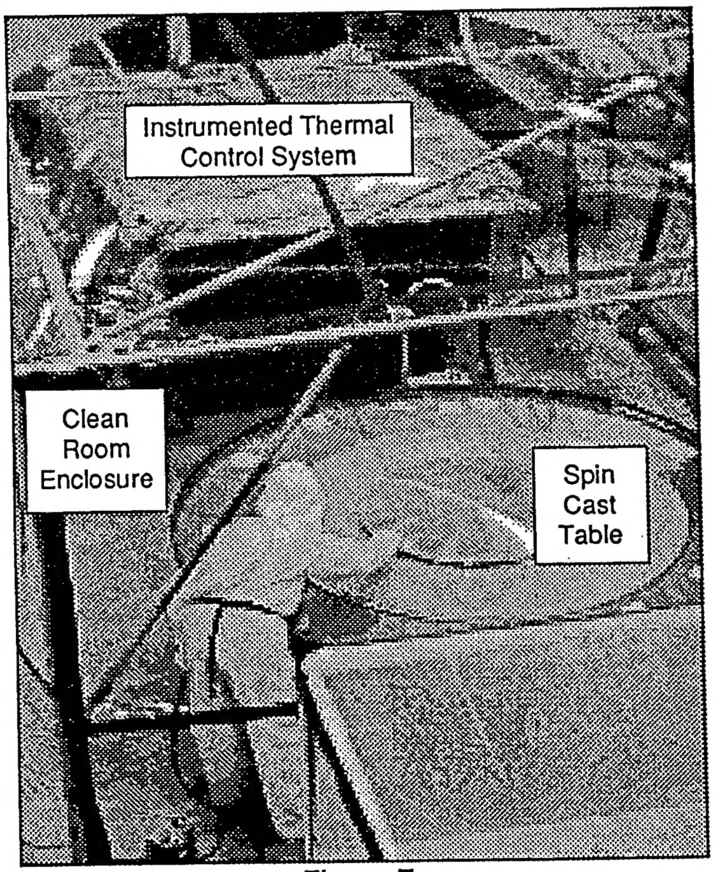

Figure 7.
Photograph of Clean Room with Spin Cast Table and Instrumented Thermal Control Systems

increased size capabilities of the casting equipment will enhance the production processes to fabricate large off-axis concentrators for the solar rocket flight article test planned in the near future.

Additional studies should be done to develop reflective surface support and tensioning technologies for future development. The current tensioning method considered the most practical technology for initial flight testing of the solar thermal rocket deployment and rigidization is the inflation method. For long-term mission survivability goals to be met, in the face of concentrator pressure window darkening and micrometeoroid puncture leakage, it is imperative that a film support tensioning technology not requiring continuous pressurization be developed. The support tensioning developed should be able to meet the specific weight and concentration ratio goals of the solar-powered rocket. Alternative technology options such as electrostatic tensioning, inflation deployed then rigidized, and elastically deployed concentrators are candidate technologies that should be further researched. All of these advanced technologies would incorporate the spin cast methods that have been developed under the current research effort.

Acknowledgements

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